Ultra-High Energy Cosmic Rays and Stable H-dibaryon

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Abstract

It is shown that an instanton induced interaction between quarks produces a very deeply bound H-dibaryon with mass below $2M_N$, $M_H = 1718$ MeV. Therefore the H-dibaryon is predicted to be a stable particle. The reaction of photodisintegration of H-dibaryon to 2Λ in during of its penetration into cosmic microwave background will result in a new possible cut-off in the cosmic-ray spectrum. This provides an explanation of ultra-high energy cosmic ray events observed above the GZK cut-off as a result of the strong interaction of high energy H-dibaryons from cosmic rays with nuclei in Earth's atmosphere.

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The cosmic microwave background (CMB) gives the GZK cut-off on possible energies of cosmic rays produced at extragalactic distances [1]. This cut-off is related to the threshold for the pion production in the proton(neutron)-CMB scattering. However, recently, some number of cosmic ray events above the GZK cut-off has been found [2]. It turns out that this experimental result cannot be explained within the Standard Model (SM) and various explanations with taking account of effects beyond SM have been suggested (see review [3]).

In this Letter we will argue another possibility to explain ultra-high energy cosmic ray (UHECR) events within SM.

The arguments are based on the consideration of influence of a complicated structure of QCD vacuum on masses of the hadron states. These effects are connected with the existence of the strong fluctuations of gluon fields called instantons in the QCD vacuum (see review [4]). The main idea is to show the possibility of a deeply bound *uuddss* H-dibaryon state [5] in the instanton field.

This H-dibaryon has vacuum quantum numbers $J^{PC} = 0^{++}$, $T = 0$ and therefore its interaction with vacuum can be very strong. The explicit consideration shows that this strong interaction is related to the very specific wave function of H-dibaryon which includes a large mixture of diquark configurations that strongly interact with instantons. In a sense, the dynamics of H-particle is similar to the dynamics of π-meson. In both cases the interaction with vacuum is very strong and leads to a large attraction between quarks. As a result, we have massless (in the chiral limit) $\pi-$meson and possibility for a small mass of the H-dibaryon.

There are a lot of calculations of the H-dibaryon mass within different models (see a discussion in [6]). The most of them predict the mass of the particle near $2M_\Lambda$ but only two of them took into account the instanton interaction between quarks [7], [8]. In [7] a rather deeply bound H-dibaryon state has been obtained with the mass $M_H = 2090$ MeV. In the calculation some specific version of the bag model has been used. In this version a very strong dependence of the confinement-force contribution to the hadron masses on the number of quarks inside hadron had been used. As the result, the mass of H-dibaryon was overestimated. In paper [8] it was argued that three-body forces induced by instantons can lead to the unbound H-dibaryon. We disagree with this conclusion. The estimation of [7] shows that only a tiny contribution of three-quark interaction to the mass of H ($\Delta M_3 \approx 5$ MeV) is possible. This suppression is due to a very small probability to find the three quarks simultaneously inside instanton.

It is very important to take account of the instanton-induced interaction in diquark configurations inside a multiquark hadron state. Many years ago it was shown that even for usual baryons, this interaction plays a fundamental role in the mass splitting between different hadron multiplets [9],[10]. This is related to the instanton-induced strong attraction between quarks in diquark configuration $q^2(\bar{3}^F, S = 0, \bar{3}^C)$. In the dibaryon state besides this configuration also the mixture of diquarks $q^2(\bar{3}^F, S = 1, 6^C)$ can lead to a large decrease of the dibaryon mass. Furthemore, it was shown recently that the instanton-induced diquark configurations are also important in connection with the possibility to have a colour superconductivity of the quark-gluon matter [11].

Let us calculate the instanton contribution to the mass of H-dibaryon. The quark-quark t'Hooft interaction induced by instantons [12] has the following structure in the flavor-colour-spin space

$$\mathcal{L}_{ins} = \sum_{i>j} \mu_{ij}(1 + \frac{\lambda_i^a \lambda_j^a}{32}(1 + 3\vec{\sigma}_i \vec{\sigma}_j)), \tag{1}$$

where $i, j = u, d, s$ and coefficients $\mu_{i,j}$ depend on the instanton density and quark masses. It was shown within the instanton liquid model of QCD vacuum that the strength of interaction (1) is enough to explain all spin-spin mass splittings between different hadronic states (see [4]).

Therefore one can consider the coefficients μ_{ij} as parameters determined by the spin-spin mass splitting between baryon states. Within the constituent quark model with instanton induced interaction which describes the masses of ground states of the octet and decuplet of baryons with an accuracy of a few MeV [10], the formula for the hadron mass is

$$M_{hadron} = N_U U + N_S S + \Delta M_{inst}, \tag{2}$$

where N_U and N_S are numbers of light and strange quarks in a hadron and U and S are their constituent masses, ΔM_{inst} is the contribution of instantons. By using the wave function of baryons, one can show that for the baryon decuplet the instanton contribution is zero and for the baryon octet it is [9]

$$\Delta M_N = -3\alpha/2,\ \Delta M_\Lambda = -(\alpha+\beta/2),\ \Delta M_\Sigma = \Delta_\Xi = -3\beta/2, \tag{3}$$

where

$$\alpha = 3\mu_{u,d}R_{00}, \quad \beta = 3\mu_{u(d),s}R_{00}, \tag{4}$$

and R_{00} is the radial matrix element of interaction (1). The best values of the parameters which provide a very good description of the baryon masses are [10].

$$U = 412.9\text{MeV},\ S = 557.5\text{MeV},\ \alpha = 200.5\text{MeV},\ \beta = 132.7\text{MeV}. \tag{5}$$

To calculate the instanton contribution to the H-dibaryon mass, one should know the dissociation of the H wave function

$$q^6 = \sum_j C_j q_j^4 \times q_j^2. \tag{6}$$

In this case the matrix element of the two-particle operator R_2 for q^6 state is

$$< q^6|R_2|q^6 >= 15\sum_j C_j^2 < q^2|R_2|q^2 > . \tag{7}$$

The dissociation has been obtained in [7] and in the basis of $SU_3^F \times SU_2^S \times SU_3^C$ it is given by the formula

$$\begin{aligned} |H(0^F,0^S,0^C)> \quad = \quad & \sqrt{\frac{1}{10}}q^4 \times q^2(6^F,0,6^C) + \\ & \sqrt{\frac{3}{10}}[q^4 \times q^2(\bar{3}^F,0,\bar{3}^C) + q^4 \times q^2(\bar{3}^F,1,6^C) + q^4 \times q^2(6^F,1,\bar{3}^C)]. \end{aligned} \tag{8}$$

By using (8) and well-known matrix elements of $\lambda_1\lambda_2$, $\vec{\sigma}_1\vec{\sigma}_2$ operators for different diquark states in (8), one can easily calculate the instanton contribution to the mass of H-dibaryon

$$\Delta M_H = -9(\alpha+2\beta)/4. \tag{9}$$

With the values of the parameters (5) the mass of H-dibaryon is

$$M_H = 1718\text{MeV}. \tag{10}$$

This mass is below $2M_N = 1876$ MeV and therefore the H-dibaryon should be *a stable particle.*

The experimental status of H-dibaryon is uncertain [13], [14]. For example, one of the best results on the H-dibaryon properties is only the upper limit for the H production cross section

obtained by BNL E836 Collabobation [14] in the mass interval $M_H = 1850 \div 2180$ MeV which is beyond of our prediction (10).

The unique properties of the H-particle should lead not only to some anomalies in the cross sections with strange particles (see a discussion in [14]) but also to fundamental cosmological consequences. One of these consequences is the natural explanation of observed UHECR above the GZK cut-off by the H-particle component in cosmic rays. The H-dibaryon has no electric charge and its spin is zero. That means that the magnetic moment of H is also zero. Therefore this particle should has a rather small cross section due to interactions with the cosmic microwave background. The H-dibaryon is the deeply bound state of two Λ. Therefore a significant part of its cross section of interaction with CMB can originate from the reaction of the photodisintegration to 2Λ. The threshold for this reaction for the mass $M_H = 1718$ MeV is approximately 7×10^{20} eV. This threshold is above the GZK cut-off and does not contradict with the available experimental data [2]. Therefore the existence of a stable H- dibaryon may explain UHECR. It only needs some source of ultra-high energy cosmic H-dibaryons. One possible source of these cosmic H-dibaryons could be their production by accelerated protons in radio-galaxies beyond GZK radius. Another, much more interesting source of high energy cosmic H-dibaryons is the phase transition from nuclear to H-dibaryon matter inside a neutron star. In this case a very large mass difference between two neutrons and H-dibaryon can lead to the explosion of a neutron star and production of ultra-high energy cosmic H-dibaryons.

In summary, a stable H-dibaryon is predicted. Its stability is connected with strong attraction between quarks due to the interaction with QCD vacuum. It is shown that ultra-high energy cosmic H-dibaryons give the explanation of the observed deviation from the GZK prediction.

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